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CONSIDERATION OF METEOROLOGICAL CONDITIONS WHEN DETERMINING THE NAVIGATIONAL WATER DEPTH OVER A SANDWAVE FIELD

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ABSTRACT

In a sandwave field in the Outer Thames Estuary, Great Britain, dune bed forms occur on the flanks and crests of the sandwaves. Studies of the dunes, as depicted by high-resolution sonar, show that the dunes are normally dominated by tidal flow conditions and that a relatively constant mean wave length (4.5 m) is maintained. In the event of adverse weather when large surface waves occur in the area, the tidal dunes are replaced by dunes with a significantly shorter wave length (1.5 m to 1.7 m). With the moderation of wave conditions the dunes progressively revert to their tidal equilibrium condition.

If such redistribution of sediments can be shown to occur on the flanks of a sandwave, then similar or greater action is to be expected in the crestal area, probably affecting safe navigational depths.

INTRODUCTION

Studies of sandwaves have been carried out in the tidal marine environment for over 100 years. Up until the 1930s, when the echo sounder was developed, most of the studies were restricted to observations in shallow water, or in areas exposed at low tide (CORNISH, 1901). With the introduction and common usage of the echo sounder, and later of sidescan sonar, it became possible to delineate offshore sandwave fields and attempt classification based upon morphology (Van VEEN, 1935). Much of the interest in sandwaves in the 1950s and early 1960s was directed towards mapping the areas of occurrence and defining directions of net sediment transport based upon cross sectional asymmetry (Stride, 1959). Attempts were made to measure lateral movement of individual sandwaves, but in many cases the results were ambiguous as possible movement, measured over a comparatively short time scale, was less than the accuracy of the position fixing system being used (Langeraar, 1966). During the late 1960s sandwaves became of considerable importance to the mariner owing to the rapid increase in size of bulk carriers and the associated requirement to navigate with a minimum of underkeel clearance (Dickson, 1967). By 1970 it was common practice for deep draught tankers, drawing up to 14.8 m, to reach the oil terminals of the Port of London having experienced underkeel clearances of approximately 1 m (White, 1972).

At Longsand Head, the point of entry to Black Deep Channel, which is the main approach route into the Thames Estuary and the Port of London, there is a sandwave field which reduces the navigational water depths of that area to 13 m below Ordnance Datum, a reduction of approximately 36% (fig. 1). Research has been carried out in the area since 1969 (Langhorne, 1973), primarily on account of its importance to the Port for the navigation of deep draught vessels. Up until 1967, Black Deep Channel remained without navigational buoys and only poorly surveyed. The preceding hydrographic survey of 1951 did not establish the existence of the sandwave field, as the echo sounding traverses had been orientated approximately parallel to the sandwave crest lines. At this time

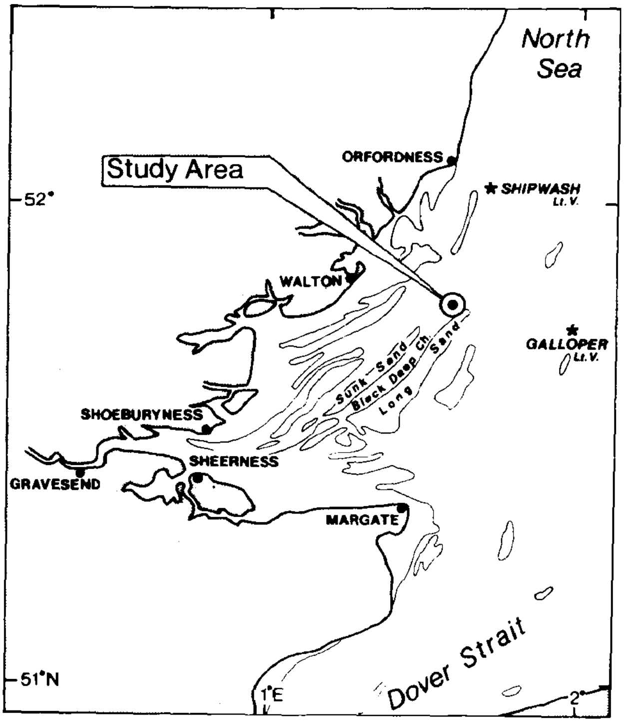

Fig. 1. — Location diagram.

it was survey practice to run survey lines *across* a channel so that the boundaries may be more accurately delineated.

For the purpose of this paper an arbitrary division has been made between sandwaves and dunes, based upon size. The term sandwave is used to refer to the large rhythmic features which are readily detected by echo sounding, whilst dunes are the smaller features, with wave lengths of up to 15 m, which occur formed in the surface sediments.

THE LONGSAND HEAD SANDWAVE FIELD

The sandwaves within the field at Longsand Head are elongated depositional ridges of non-cohesive sediment, orientated with sinuous crest lines approximately at right angles to the dominant tidal flow directions. Maximum sandwave heights reach 7.3 m. In different areas of the field they may be symmetrical or asymmetrical in cross-sectional profile, with lee slopes facing both into and away from the flood tide. Lee slopes, or maximum slopes in the case of symmetrical sandwaves, do not approximate to the angle of repose of sediment in water (28°- 32°). Mean lee-slope angles between crest and trough measured from scale-corrected echo sounder records exceptionally reach 15°, whilst the average slope from some 110 measurements is 8.4°. The sandwaves are relatively stable features, and individuals may be recognised by their form and position from 1967 until the present day (1976). Lateral movement of the gross sandwave forms remains ambiguous since measured values are not significant relative to the accuracy of the Decca Hi-Fix position fixing system which has been used throughout the studies.

The position of the sandwaves in relation to the neighbouring banks and coastline is such that long unimpeded wave fetch only reaches the area from the north east. From this direction occasional, but severe, gale-force winds occur. It is also the direction approximately parallel to the flood tide.

Dune bed forms, which are secondary in size to the major sandwave, are common throughout the sandwave field and also in extensive areas of relatively level sea bed to the south of the field in Black Deep Channel. The dunes, with wave length of up to 15 m and height of up to 1.0 m, are not readily detected by echo sounding as their height is comparable with that of unrecorded ship's motion. In no case, however, have sidescan sonar records revealed sandwaves which are free from dunes. Measurements made from scale-corrected sonar records show that, though the dunes are normally orientated parallel to the sandwave crest lines, exceptions are common; and divergent angles of up to 80° have been recorded. There is a tendency for dunes to decrease in size close to the crests of the sandwaves, probably in association with the high shear stresses which occur in this area on both flood and ebb tides. Under tidal conditions, there does not appear to be any other obvious relationship between dune size and position on the flank of a sandwave (fig. 2). Figure 3 shows that though the dune size often decrease close to the sandwave crestline, exceptions are not unusual. Cloet (*personal communication*), carrying out close-line (13.5 m)

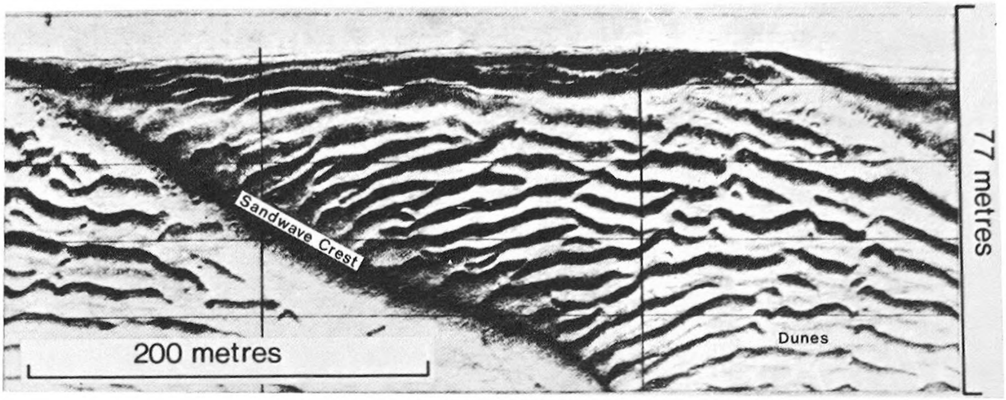

FIG. 2. — Sidescan sonar record showing dunes in tidal equilibrium on the flank of a sandwave.

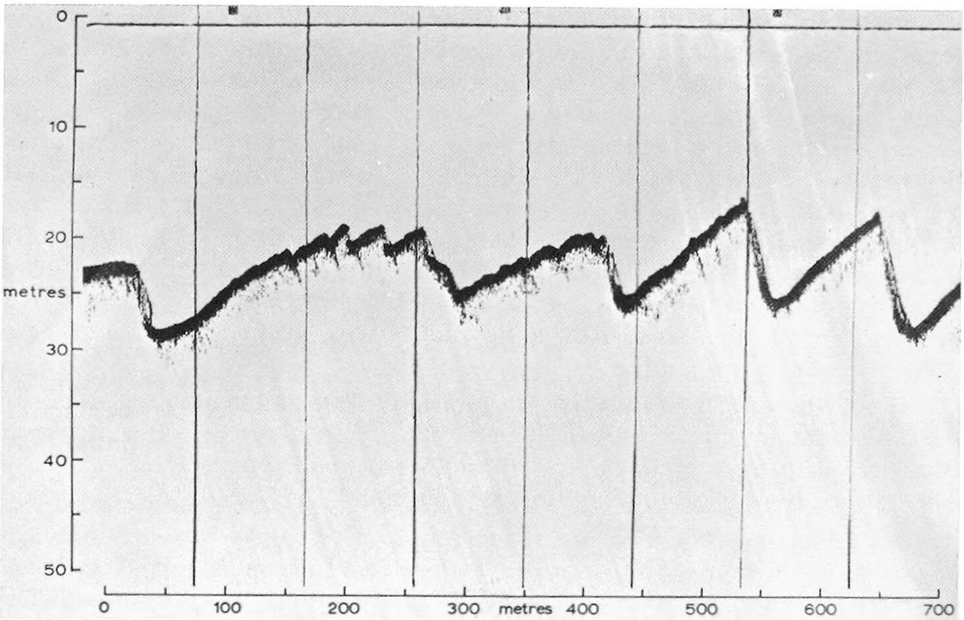

FIG. 3. — Echo sounder record showing the occurrence of dunes on sandwaves.

echo sounding traverses across sandwaves in the Sandettie area shows that height undulations on individual sandwave crests may reach 1.4 m. Though these may not be directly attributed to the presence of dunes on the crestlines, they do indicate that such variations in sandwave height are to be expected.

Diver observations reveal that dunes, unlike the large-scale sandwaves in the Longsand Head area, maintain lee slopes which are close to the angle of repose of sediment in water. Slight disturbance causes these slopes to avalanche.

It is considered that the steepness of slope of a sandwave or dune is important in that it is indicative of the relative activity of the feature. In those cases where the surface of a sandwave is completely carpeted in dunes, any change in form or change in position of the gross sandwave will be the resultant of the changes which have occurred in the dunes, or sediment passing through the dune regime. In agreement with ALLEN & COLLINSON (1974) it is accepted that at any one time there is only one active bed form, though morphologically two or more may be identified.

DUNE STUDY AREA

In order to study the temporal stability of dune bed forms, an area within the sandwave field was selected for detailed observations. The selected area lay on the stoss slope of a sandwave of some 4 m in height, the water depth above the crests being approximately 12 m. A sediment sampling programme indicated that the mean grain size of the sediment in this area ranges from 1.25 ϕ to 0.75 ϕ (medium to coarse sand, 425-600 microns).

FIELD DATA

Sidescan Sonar

EG&G Dual Channel sidescan sonar (frequency 110 kHz, pulse length 0.1 ms) was used extensively to map the relative distribution and configuration of the dunes in the research area.

In order to obtain repetitive sonar cover of the same area of the sea bed the Port of London Authority Hi-Fix Chain was used for position control. Using this system it was estimated that the same ship's track could be navigated to a repeatable accuracy of better than 10 m (LANGHORNE & HOOPER, 1974). This accuracy was acceptable in consideration of the dual channel sonar range of 154 m (500 ft) which was used. On well controlled tracks, in good sea conditions, the high-resolution sonar gave records of sufficiently high quality that individual dunes could be positively identified from one traverse to the next. Morphologically, dune recognition is made possible by their individual form characteristics and interrelationship with neighbouring dunes (fig. 2).

Accurate measurements of dune wave length can only be obtained from sonar records if corrections are made for slant range and ship's speed over the ground (FLEMMING, 1976). Having applied these corrections, statistical values of dune wave length were obtained by both Quantimet Image Analyser (*) and manual methods.

Wave Recording

From 1973 onwards wave data was made available by the Port of London Authority. During this period wave recording was carried out on

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(*) Image Analysing Computers Ltd., Melbourn, Royston, Herts, England.

Sunk navigation buoy 4.5 km from the research area. A standard Waverider sensor (*) was installed on the buoy (for safety from passing shipping) and the wave data was transmitted via Walton Pier to the Port control at Gravesend. Calibration was necessary in order to obtain accurate data from the response of the navigation buoy. Acceptable results were obtained from waves of larger amplitude and period, which are the waves which have significant effect on the sea bed at 12 m depth.

To obtain an indication of the possible effect of wave action at the sea bed, an approximate particle oscillation velocity at a given depth can be calculated using AIRY's (1845) equation :

$$U_m = \frac{\pi H}{T \sinh(kh)} \qquad (1)$$

in which

T = wave period
k = wave number = $2\pi/L$
h = water depth
L = surface wave length
H = wave height (crest-to-trough)
U_m = maximum oscillation velocity at the sea bed

In order to make a quantitative comparison of the different periods of adverse weather, oscillation velocities at the sea bed are calculated using values of significant wave height (mean height of highest one third of recorded waves) and corresponding period obtained from the analogue wave records. (To get more accurate results spectral methods must be used (HADLEY, 1964), but for the present purposes the basic method used here gives adequate results).

Tidal Flow

Tidal flow data was recorded over an 18-day period at a height of one metre above the sea bed, in a position in the trough between the sandwaves, using a bottom-mounted self-recording current meter. A summary of the analysis of the data is shown in figure 4. Taking a critical erosion velocity (at 1 m) of 30 cms^{-1} for coarse sand (0.5 ϕ) (SOULSBY (*in press*) after SHIELDS (1936)), assuming a logarithmic velocity profile and a roughness length of 0.25 cms, the flood tide exceeds the critical velocity for 38% of the period of a tidal cycle, whilst the ebb tide only exceeds the critical velocity for 26% of the period. Both maximum flood and ebb velocities reach 60 cms^{-1}, but in each case for less than 1% of the period.

Grain Size Distribution

The grain size distribution within the sandwave field was obtained by sieve analysis (0.25 ϕ interval of sieve sizes) of sediment samples obtained by both grab sampling and vibrocoring.

(*) Datawell b.v. Laboratorium voor instrumentatie, Zoomerluststraat 4, Haarlem, Netherlands.

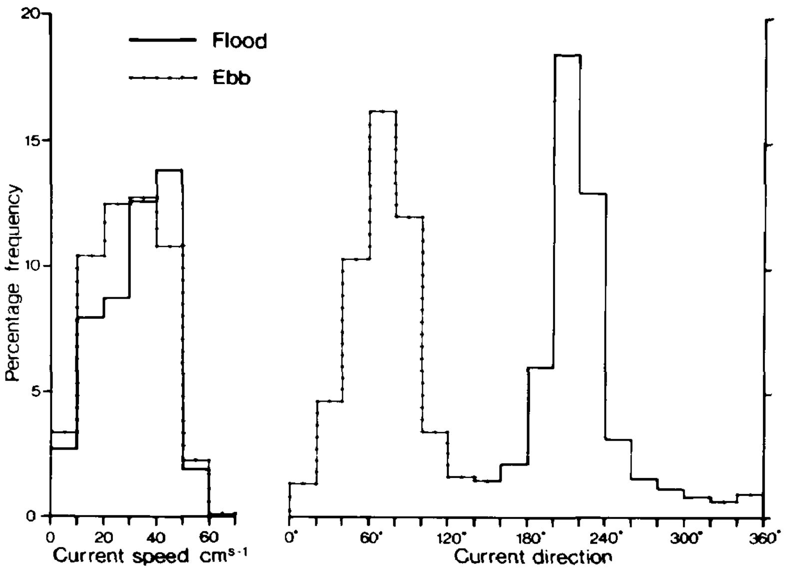

FIG. 4. — Tidal flow data. Recorded over an 18-day period at a height of 1 metre above the sea bed, in a position in the trough between sandwaves.

ANALYSIS OF FIELD DATA

During the period 1971 to 1974 sidescan sonar data was obtained over a standard track which was orientated approximately parallel to the dune crest lines in the study area. The majority of sonar records showed a relatively constant dune pattern with a mean wave length of 4.5 m ± 0.3 m. Repetitive observations over a two-day period failed to show any indication of reversal of asymmetry during the course of successive flood and ebb tides. Records obtained over a six-day period, free from adverse weather (i.e. calculated wave-induced oscillation velocities at 12 m depth never exceeded 14 cms^{-1}) showed that individual dunes maintained their identity over such periods. Over a longer time scale, July to October 1971, the calculated mean wave length changed from 4.5 m to 4.2 m (standard deviation 1.8 m and 1.5 m respectively) but it was not possible to identify, with confidence, any individual dune from one survey to the next. During this period no wave data was available but meteorological data suggested that effective wave action was probably of minor importance as wind speeds never exceeded 25 knots when blowing from the North or East, the directions of long wave fetch.

During the period of study, three sequences of observations were obtained which require more detailed description, namely:

March 1972

In March 1972 sonar observations in the research area had to be delayed on account of adverse weather. Meteorological observations at

Shoeburyness recorded mean wind speeds of in excess of 20 knots for a period of 71 hours from a direction of between 060° and 100° (surface wave fetch 120 to 65 miles). Similar conditions were recorded at Galloper and Shipwash light vessels.

The only sonar data available was obtained some 5 days after the climax of the gale (gale max. + 123 hours) (fig. 5). The record shows that the tidal current dune pattern normally associated with the area had been completely replaced by a pattern of dunes with similar orientation but of considerably shorter wave length.

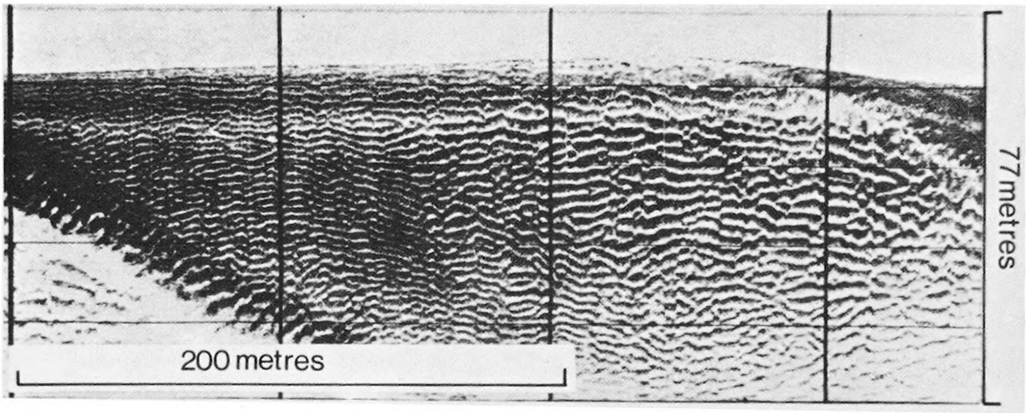

FIG. 5. — Sidescan sonar record showing wave induced dunes (Gale max. + 123 hours).

Analysis of dune wave length from figure 5 shows that with increase in water depth there is a tendency for a decrease in dune wave length.

Calculated mean wave length in the near-crest zone = 3.1 m
Calculated mean wave length at mid-slope = 2.6 m
Calculated mean wave length in the trough = 1.7 m

This conclusion supports the findings of INMAN (1957), HARMS (1968) and KOMAR (1974) for wave-generated dunes.

May 1973

Repeat sonar surveys were planned on a daily basis between 8 and 20 May 1973. On 16 and 17 May, sea conditions prevented observations. During this period meteorological observations at Shoeburyness recorded mean wind speeds of in excess of 20 knots for a period of 36 hours from a direction of between 060° and 90° (surface fetch 120 to 80 miles).

Wave records obtained at Sunk Buoy showed that the maximum wave height reached 2.90 m whilst the significant wave height reached 1.80 m with a corresponding period of 5.56 seconds. Using values of significant wave height and period with the equation given, the maximum calculated oscillation velocity at the sea bed (12 m) reached 39 cms^{-1} and remained in excess of 26 cms^{-1} for a period of 16 hours. These calculated velocities occurred superimposed upon a tidal flow velocity which, as previously stated, can reach 60 cms^{-1}.

Oscillation velocities derived from wave records obtained for the remainder of the survey period on no occasion exceeded 14 cms^{-1} at 12 m water depth and therefore were of little significance in terms of sediment movement.

By comparison of sonar records, individual dunes could be identified over the six day period prior to the adverse weather. The mean wave length remained relatively constant and comparable with records obtained on other occasions. (Mean wavelength 4.5 m ± 0.2 m). Sonar records obtained in poor sea conditions on 18 May, the first opportunity after the adverse weather, revealed the presence of short wave length dunes (< 1 m) superimposed upon the larger tidal dunes, with some suggestion of the latter forming double crests. Records obtained two days later confirmed the formation of double crests whilst no evidence remained of the presence of short wave length dunes (fig. 6).

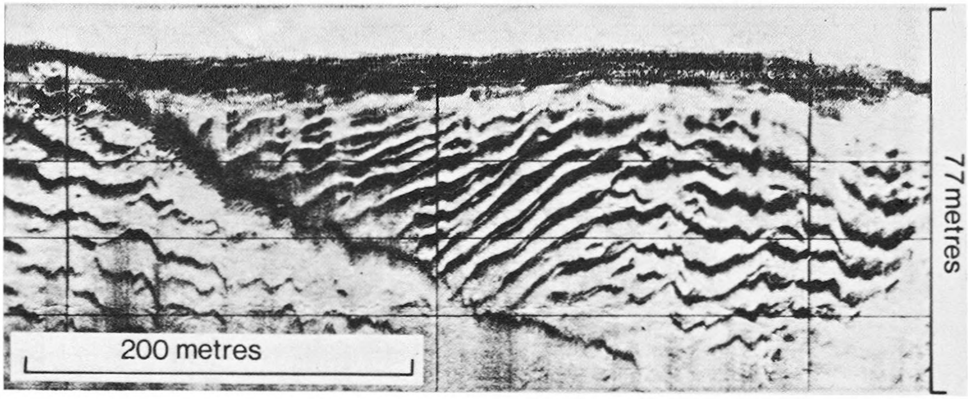

FIG. 6. — Sidescan sonar record showing tidal dunes partly modified by surface wave action.

Dune comparison — Post gale sequence

A further sequence of sonar data was obtained in October and November 1974. On 16 October it was established that the tidal dune configuration was present. Adverse weather occurred 22-24 October, and again 29-30 October. The magnitude of the gales and the resulting wave conditions are summarised in Table 1.

The first of a series of post-gale sonar surveys was conducted on 31 October 2nd gale max. + 35 hours). Analysis of the data showed that, as is the case with the March 1972 data, the tidal dunes had been replaced by short-wave-length wave-induced dunes (λ crest = 1.72 m, λ mid-slope = 1.67 m, λ trough = 1.55 m). Six further sonar surveys were carried out terminating on 7 November (2nd gale max. + 203 hours). During this period the sonar records showed an increase in dune wave length of up to approximately 70% (trough) to 80% (crest) of the normal equilibrium tidal-dune wave length.

TABLE I

	22 - 24 October	29 - 30 October
Wind :		
Direction	330 - 040°	270 - 330°
Fetch	10 - 450 N Miles	9 - 11 N Miles
Mean speed	> 20 Kts for 24 hours	> 20 Kts for 44 hours
Waves :		
Significant wave height	0.8 - 2.8 m	1.2 - 2.0 m
Period	3.7 - 6.1 sec	3.8 - 5.4 sec
Oscillation velocity (at 12 m)	> 25 cms^{-1} for 34 hours > 35 cms^{-1} for 27 hours	> 25 cms^{-1} for 21 hours > 35 cms^{-1} for 4 hours.

DISCUSSION

The field data obtained indicates that, in the particular area within the sandwave field at Longsand Head, the dune regime is controlled by both the tidal flow and wave conditions. Most of the data indicates that the tidal dune regime is dominant and this "equilibrium condition" may prevail for several months without destruction. During periods free from wave action the tidal dunes, within the specified area, maintain a relatively constant mean wavelength (4.5 m ± 0.3 m) though the dunes undergo gradual change. It can be shown that the rate of change is such that the individual dunes can maintain their sonar identity for periods of six or more days.

In the event of adverse weather, the combined effect of wave energy superimposed upon tidal flow can destroy the prevailing dune bed forms. The mechanics of destruction are probably bottom shear stresses exceeding the upper threshold for dune stability (MANOHAR, 1955) and pressure fluctuations causing loss of soil strength in the surface sediments, resulting in slope instability and slumping (MITCHELL, TSUI & SANGREY, 1972). As wave conditions moderate, the velocities become less than the upper threshold for dune generation, and dunes with wavelengths related to the wave-induced orbital diameter and the grain size of the sediment will be formed (INMAN, 1957; KOMAR, 1974). With further reduction of wave energy the influence of the tidal velocities becomes dominant and the dunes increase in wavelength until the tidal dune equilibrium is attained.

The seven successive sonar surveys carried out during the post gale period in October and November 1974 show the increase in mean wavelength over the period of gale maximum + 35 hours to gale maximum + 203 hours.

If it is assumed that, following reversion to tidal current control, the dune wavelength develops according to the equation :

$$\lambda = \lambda_1 \, [1 - \exp \{-(t - t_0)/\tau\}] \qquad (2)$$

in which:

λ = the mean wave length calculated from the seven surveys for positions near the crest of the sandwaves, at mid-slope and in the trough

λ_1 = the equilibrium wave length (4.5 m)

t = the time in hours for each of the seven surveys from the time of gale maximum

t_0 = the time of hypothetical zero wavelength

τ = a time constant

(t_0 and τ were obtained by plotting log $\lambda_1/\lambda_1 - \lambda$ against time), then an approximate rate of increase in wave length of dunes may be obtained (fig. 7). The goodness of fit of the calculated wave lengths is subject to both the quality of the sonar records and also further periods of minor wave influence. For example, calculated oscillation velocities reached 23 cms^{-1} at 12 m depth on 4 November (gale max. + 132 hours).

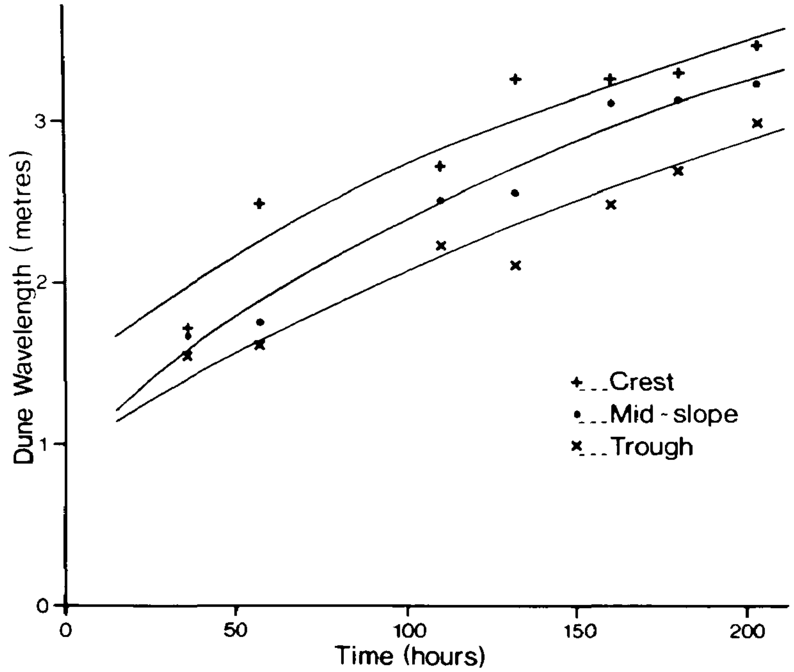

FIG. 7. — Reversion of dune wave length measured from sidescan sonar records.

Using the recovery rate as obtained in equation 2, a wavelength/depth/time graph may be plotted (fig. 8) which suggests that 50 % of the equilibrium wave length was attained in approximately 60 hours near the crest of the sandwave, in 90 hours at mid-slope and in 120 hours in the trough, whilst 90 % recovery was attained in 340, 400 and 520 hours respectively.

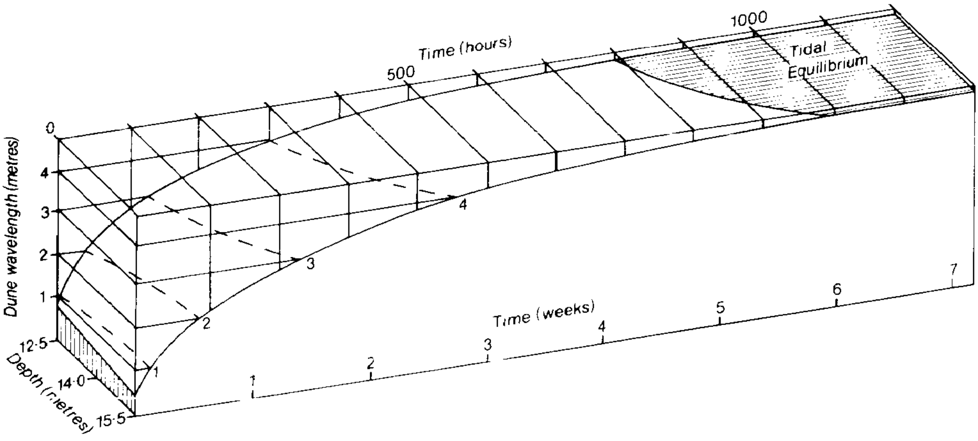

FIG. 8. — Reversion of dune wave length as a function of depth and time.

Both the March 1972 and May 1973 sequences of data are important for the understanding of the conditions required to generate particular dune formations. The former, which consists of one sonar record, confirms that the events of October and November 1974 are not unique. Calculated wave lengths, for positions near the crest, at mid-slope and in the trough (3.1 m, 2.5 m and 1.7 m respectively) at the time of gale maximum + 123 hours, when compared with those of October and November 1974 give a good correlation at the positions near the crest and at mid-slope, but not at the trough position (3.0 m, 2.7 m and 2.4 m respectively). The poor correlation in the trough position could be the result of a change in water depth, hence a change in wave-induced orbital diameter, and/or change in grain size of the sediments.

The May 1973 data gives an indication of the wave conditions required to bring about a partial change in dune configuration, as opposed to the complete destruction and reformation which probably occurred in both March 1972 and October and November 1974.

CONCLUSION

During periods of intense wave action superimposed upon tidal flow, the dunes on the flank of a sandwave at Longsand Head are destroyed and subsequently replaced by dunes with considerably shorter wavelength. Under tidal conditions the dunes are regenerated to their tidal configuration over a period of 14 or more days. If such redistribution of sediments occurs on the flanks of a sandwave, then a similar or greater action is to be expected in the crestal area, where both the wave energy and shear stress exerted by the tidal flow will be greater. The field data does not exist to make it possible to quantify the changes which occur in crestal height, but consideration should be given to the preceding wave conditions when undertaking accurate bathymetric surveys in a sandwave area.

ACKNOWLEDGEMENTS

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